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Visual Strategies Underpinning the Spatiotemporal Demands During Visuomotor Tasks in Predicting Ball Direction

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(Article begins on next page)

1 **Title: Visual strategies underpinning the spatiotemporal demands during visuo-motor tasks in**
2 **predicting ball direction**

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4 **Introduction**

5 Team sports are often characterized by spatiotemporal constraint that necessitates the processing of
6 and responding to visual information in a limited time frame (Panchuk & Vickers, 2006).
7 Consequently, spatiotemporal constraints are present in different sporting situations, such as when
8 the athlete's response time, combined with the distance the ball will travel prior to being intercepted,
9 exceeds the ball flight duration (Piras, Lanzoni, et al., 2016). In these conditions, successful
10 performance is based upon the athlete's accurate allocation of visual attention and subsequent
11 decision making prior to initiating a motor behaviour, either at the instance of or immediately after a
12 key action (e.g., the ball being kicked in a soccer penalty kick; Piras et al., 2020; Piras & Vickers,
13 2011).

14 In competitive sports, in which precise and correct prediction of the intentions of others are a
15 fundamental component of performance, attending to and processing visual information are key
16 determinants of successful motor execution (Williams, 2009). Indeed, in fast ball sports like table
17 tennis (Piras, Lanzoni, et al., 2016), as well as in team sports such as soccer (Piras et al., 2020; Piras
18 & Vickers, 2011; Timmis et al., 2018) and volleyball (Piras et al., 2010; Piras, Lobietti, et al., 2014),
19 the need to perceive the intentions of the opponent occurs under severe time pressure. This time
20 pressure will be impacted by the distance the object travels once being struck/hit and being
21 intercepted, for example a ball being kicked from different distances (Navia et al., 2017; Panchuk &
22 Vickers, 2006). In a recent article, Navia et al. (2017), comparing expert futsal goalkeepers
23 intercepting penalties taken from 10m in comparison to 6m, reported that more saved penalties
24 occurred when kicked from 10m, with goalkeeper's initiating their movement later, looking for longer
25 towards the ball with respect to the penalty takers' body. In ice hockey, when goaltenders were

26 required to save shots taken from 5m with respect to 10m, the number of saves was not significantly
27 affected by the different distance from which the shot was taken and there was no difference in visual
28 search behaviour between distances (Panchuk & Vickers, 2006).

29 Although differences in fixation locations through expertise have been reported in the majority of
30 studies (for a review see Mann et al., 2007), a paucity of research has investigated differences between
31 the utilization of the fovea with respect to the periphery during spatiotemporal constraints (Vater et
32 al., 2019). Because of the different functional organization of foveal and peripheral visual field (Raffi
33 & Piras, 2019), the cue's proximity could influence the utilization of the foveal or the peripheral
34 vision to pick-up relevant information necessary to make predictive judgements early in time, just
35 before the initiation of the motor response (Williams, 2009).

36 Saccadic eye movements bring objects of interest into the fovea, where the visual resolution is
37 highest. During the visual perception of extrafoveal cues, before the eyes start to move, peripheral
38 vision is enhanced, and sensory orientation is restructured by the saccade target location (Piras, Raffi,
39 et al., 2016). These changes occur rapidly, with an influence on the visual perception, as humans
40 perform saccades every few hundred milliseconds (Klein & Ettinger, 2019). However, saccades are
41 not only made to reorient the fovea. Small saccades, termed microsaccades, occur during fixation,
42 with a relatively high rate once the object of interest is foveated (for more information see Martinez-
43 Conde et al., 2013). It has been found that microsaccades serve the function of preventing visual
44 fading during fixation, help in maintaining accurate fixation on point, redirect a preferred small locus
45 on the retina and facilitate fine spatial judgments (Poletti & Rucci, 2016). Close investigations have
46 revealed that the eyes are never stationary, during fixations these microsaccades continuously upset
47 the gaze position. These movements occur even when attempting to maintain steady fixation on a
48 single point during a sport situation (Piras et al., 2015).

49 The previous work conducted by Navia et al. (2017) and Panchuk and Vickers (2006) which
50 investigated how visual search behaviour changed dependent upon goalkeeper-object distance did not

51 consider the subtle eye movements that may occur prior to goalkeeper movement initiation. In a
52 recent study, Piras et al. (2020), investigated the role of microsaccades, saccades, and pupil diameter
53 during the period that proceed a soccer goalkeeper's movement time in a penalty kick. The authors
54 identified that both saccades and microsaccades (inside 3° of visual angle) occurred during fixation
55 (i.e. quiet eye threshold, for more information see Vickers, 2007). Moreover, they found that
56 microsaccades anticipated the goalkeeper's direction, suggesting that they are not casual, but directed
57 toward the focus of (covert) attention (Hafed & Clark, 2002). Additionally, the authors demonstrated
58 a positive correlation between pupil dilation with the proximity of the motor response. Pupils reached
59 the largest size just before goalkeeper's movement initiation, increasing visual sensitivity to optimize
60 perceptual processes. Task-evoked pupil dilation in well-controlled experimental settings has been
61 referred to as an index of the allocation of cognitive control during mental activity (Beatty, 1982) and
62 in sport settings (Campbell et al., 2019). The advances in neuroscientific methods has further
63 strengthened our understanding that pupils dilate during mental activity, and that pupillometry is a
64 well-established technique for investigating human cognitive processing (Beatty, 1982). Indeed, pupil
65 size can be used as a signal of the relative amount of cognitive effort used to achieve a task and can
66 be referred to as an index of the brain activity. Campbell et al. (2019) found that golfers, during a
67 putting task, exhibited pupil dilation changes of about 30% from baseline. Additional research is
68 needed to consider the importance of the spatiotemporal constraints on the individuals' functional
69 behaviours during performance. Specifically, the aim of the present study was to examine the visual
70 search strategy of soccer goalkeepers in attempting to predict penalty kick direction taken from
71 different distances (near versus far) and from different angles of approaching the ball (left versus
72 right). We hypothesize that, when the distance from the ball is higher, and the image of the kicker
73 with the ball is smaller (i.e. subtends a smaller region of the visual scene), the goalkeeper will utilize
74 a different visual search strategy with respect to the situation in which the kicker and the ball are
75 closer (and subtends a larger region of the visual scene). We suppose that an increased distance
76 between the opponent and the goalkeeper will result in relying on information extracted via the fovea,

77 conversely, when the opponent is closer, the goalkeeper will utilize peripheral vision to monitor
78 players' movements (Williams et al., 1994; Williams & Davids, 1998). Moreover, we can hypothesize
79 that, if the kicker's run-up is an important movement phase for the goalkeeper intercepting the ball,
80 different penalty taker run-up starting point (left versus right angle of approach) could influence the
81 microsaccade/saccade orientations. The emergent search pattern in these situations would appear to
82 be at least partly constrained by the relative distance between player, the ball, and with the angle of
83 approaching the ball. Several studies have found that using the fovea and/or the peripheral vision
84 enables successful prediction of a sporting action and can be detected through microsaccades and
85 saccades (Piras et al., 2015, 2019; Piras, Raffi, et al., 2016). We presume that if more saccades are
86 performed, it should be understood to be automatically induced by the change event for foveal
87 detection; however, the absence/reduction of saccades in favour of microsaccades (fewer fixations of
88 longer duration), would rather favour the participants' ability to use peripheral vision to detect change
89 events (Piras et al., 2020; Vater et al., 2019). Due to the supposed relationship between ocular
90 movements, visual perception, and direction of attention, the present study investigated the role of
91 saccades, microsaccades and pupil-size of soccer goalkeepers during the prediction of a penalty kick
92 in two different spatiotemporal constraints.

93 **Methods**

94 **Participants**

95 Eight intermediate-level male goalkeepers with a mean age of 23.5 (± 5.2) years, one right footed male
96 kicker of 28 years and one left footed male kicker of 26 years old volunteered for the experiment.
97 Based on the effect size ($d_z = 0.80$) evident on other studies (Piras et al., 2020; Piras & Vickers,
98 2011), G*power, version 3.1.9.2 (Kiel, Germany), predicted that a total sample size of 7 would give
99 appropriate power ($1-\beta$ err prob 0.80) to detect a significant difference at alpha level of 0.05. One
100 additional participant was included to guarantee availability of data in case of missing values. At the
101 time of the study, the goalkeepers had been playing soccer for 14.7 years, and trained on average 3.5

102 times, 7 hours per week, with a competitive match at the end of the week (national level). Goalkeepers
103 reported that they have been playing recreational futsal, with competitive matches at regional level.
104 They self-reported a normal vision, and after receiving oral and written information concerning the
105 study protocol, all participants gave their written informed consent to participate in the study. The
106 study was approved by the Bioethics Committee of the University of Bologna.

107 **Stimuli and procedure**

108 A right footed male kicker was filmed, from the participants' (goalkeepers') perspective, with a
109 digital video camera (Casio® 300 frames/s, with a max resolution 1280 × 960 pixels) positioned in
110 the middle of a standard, full sized (7.32 m wide and 2.44 m height), soccer goal, with the ball (size
111 5) positioned 11m from the centre of the goal. The kicker was required to start his run-up from the
112 right of goalkeeper's perspective, at least 4 m behind the ball using the same approaching angle for
113 all penalty kicks. Ten penalty kicks were filmed and subsequently subdivided in five directed to the
114 right and five to the left (goalkeeper's perspective).

115 The same procedure was used for penalties kicked in a futsal court. A left footed male kicker was
116 filmed, from the goalkeeper's perspective, with the same video camera positioned in the middle of a
117 standard, full sized (3 m wide and 2 m height) futsal goal, with the ball (size 4) positioned 6m from
118 the penalty spot. The kicker was required to start his run-up from the left of goalkeeper's perspective,
119 at least 4 m behind the ball using the same approaching angle for all penalty kicks. Ten penalty kicks
120 were filmed and subsequently subdivided in five directed to the right and five to the left (goalkeeper's
121 perspective).

122 The experiments were performed in the dark. Stimuli were back-projected (Epson EB-W12, 720 ×
123 486 resolution; frame rate 60 Hz) onto the translucent screen positioned 300 cm away. The screen
124 covered 135 × 107° of visual field and was placed 170 cm from the goalkeepers' eyes, who stood in
125 front of the screen ready to predict the ball direction as they were in the soccer pitch. The brightness
126 of the screen was measured using a United Detector Power meter (model 351) equipped with a

127 photosensor (model 263), necessary to identify the different portions of the video clips (field of play;
128 penalty takers' body; the ball). The brightness of the screen was almost equal through the videoclips
129 ($p=0.25$; $d=0.50$).

130 The videos were presented from when the kicker started approaching the ball up to the ball passing
131 to the right or to the left of the goalkeeper's point of view. The goalkeeper was required to predict the
132 direction of the ball moving laterally (left or right) as they would on a soccer pitch, but without diving.
133 In total, each participant faced 60 penalties, 30 kicked from 11m and 30 kicked from 6m. We
134 subdivided penalties in six blocks with the same ten videoclips, with each block interspersed by 5
135 minutes of rest. Each clip had a mean duration (\pm SD) of 6046.80 ± 2.89 ms (max value of 6051 and a
136 min value of 6043 ms). The direction of the soccer shots was completely randomized but the same
137 randomised order was used for each participant. Overall, a total number of 480 clips were analysed.

138 **Eyes and body movement recording**

139 We recorded binocular eye movements with a video-based eye tracking system (EyeLink® II, SR
140 Research) comprising of two miniature cameras mounted on a leather-padded headband. Pupil
141 tracking was performed at 500 samples/s, with a gaze resolution $<0.005^\circ$ and noise limited to $<0.01^\circ$.

142 We calibrated the eye tracker at the beginning of the experiment and after each block of 10 videoclips.
143 Then, we performed data validation and drift correction by applying a corrective offset to the raw eye
144 position data after every clip. Calibration and validation of the system was repeated every time
145 possible measurement error occurred due to participants' movements. The accuracy of the eye
146 positions was checked after every clip, and if required, a drift correction was performed. Practice,
147 calibration, validation and data collection took ~ 60 minutes per participant.

148 Two inertial sensors (Cometa Systems, Italy) were placed on the goalkeepers' right and left anterior
149 superior iliac spine to collect lateral body movement. Inertial sensors (IMU; inertial measurement
150 unit, composed of a triaxial accelerometer, gyroscope, and magnetometer) were synchronised with

151 the EyeLink system (TTL trigger signal input via the parallel port) in order to have corresponding
152 goalkeepers' eyes and body movement data. In the present study, only measurements of the triaxial
153 accelerometer were considered and collected at 1000 Hz, then re-sampled at 500Hz to have body and
154 eye movements synchronized. Goalkeepers' body movement response to ball interception was
155 considered to occur if the processed IMU signal exceeded a threshold of 3 standard deviations (SDs)
156 above the baseline (preactivation) triaxial accelerometer signal. If a response was detected, a value of
157 one was assigned, otherwise zero was assigned (The Shewhart threshold, for more details see Stokes
158 et al., 2006). The latency was measured as the time from the start of the trial to onset of the body
159 movement response.

160 **Data analysis**

161 Goalkeepers had to react in a time comprised between <150-250> ms after foot-ball contact,
162 otherwise trials were classified as missed, due to early or delayed movement necessary to intercept
163 the ball (average human reaction time). Then, we selected, from the entire trial duration (6000 ms),
164 the duration of each trial for analysis, using the exact time in which goalkeepers started their final
165 movement, going back for 4000 ms, in order to have trials of the same length.

166 ***Response accuracy and movement time.*** Response accuracy (predicted/missed penalties) and the
167 final movement time, that is the time in ms from the trial start to goalkeepers' final movement to
168 predict the ball were analysed separately using a distance (11m; 6m) x response accuracy (predicted;
169 missed) ANOVA with repeated measures on all factors.

170 ***Visual search order.*** We analysed the mean number of fixations on each interest areas every 1000ms
171 (epochs), starting from the exact time in which goalkeeper's final movement initiation, going back
172 for 4000 ms (1000ms; 2000ms; 3000ms; 4000ms). This was the search sequence used by the athletes.
173 We analysed the gaze positions in relation to the positions of the moving objects using dynamic
174 interest areas, that represent the position and dimensions of important visual scene content over time
175 (Piras, Lanzoni, et al., 2016). For this purpose, the screen was divided into five interest areas (IAs):

176 (I) the HEAD of the kickers; (II) the TRUNK of the kicker; (III) the LEGS of the kicker; (IV) the
177 VISUAL PIVOT, a location in the middle between the ball, the kicking leg and non-kicking leg (Piras
178 & Vickers, 2011); (V) fixations on the BALL. All fixations outside these IAs were referred to as
179 “OUT” fixations. The mean number of fixations on each interest areas were analysed in block of
180 temporal sequences (four epochs) using epoch (1000ms; 2000ms; 3000ms; 4000ms) x condition
181 (11m, 6m) ANOVA with repeated measure on all factors.

182 ***Microsaccade/saccade characteristics.*** We considered fixation when the gaze was stable inside 1° of
183 visual angle for a minimum of 100 ms. Microsaccades were defined as eye movements $\leq 1^\circ$ in
184 amplitude, with a peak velocity $\leq 100^\circ/\text{sec}$, and that followed the same peak velocity versus amplitude
185 curve as large saccades. Microsaccades and saccades were identified using the algorithms of Otero-
186 Millan et al. (Otero-Millan et al., 2014). The clustering method of the algorithm finds, automatically
187 and objectively, a boundary between true microsaccades and non-microsaccadic events, including
188 artifacts such as head movements and changes in pupil size. For our study, we considered only
189 microsaccades occurred simultaneously in both eyes during at least 3 data samples (6ms). We
190 excluded 200 ms before and after each blink as well as when the pupil was still partially occluded.
191 Microsaccade and saccade amplitudes, durations, and peak velocities were first calculated for each
192 goalkeeper in each condition (penalties from 11m and from 6m; predicted and missed penalties)
193 separately. Then, the values of all athletes in each condition were averaged. Microsaccade rates were
194 calculated considering the duration of each clip (4000 ms). A response accuracy (2) x condition (2)
195 ANOVA with repeated measures on all factors was performed separately to analyse microsaccade
196 and saccade rate, amplitude, duration, and peak velocity.

197 Moreover, saccade and microsaccade rate (number per second) was averaged over all trials of 8
198 participants and obtained a mean rate of about one per second (computed within a moving window
199 of 200 ms). Next, we subdivided the saccades/microsaccade rate in four epochs (1000; 2000; 3000;

200 4000 ms) in order to analyse them with repeated measures ANOVA with epochs as within-subjects
201 factor and condition (11m; 6m) as between-subjects factor.

202 ***Microsaccade/saccade orientation.*** We computed the two-dimensional distribution of all
203 microsaccade and saccade directions in the two different goalkeeper's movement direction (right,
204 left), subdivided in penalties kicked from 11m and from 6m. We performed the Watson-Williams test
205 for homogeneity of means (Oriana® 4.0) in which the null hypothesis was that the orientations of
206 microsaccades and saccades between penalty condition (11m versus 6m) have similar continuous
207 distribution at the 5% level of significance. Furthermore, analysis considered response accuracy
208 (predicted, missed) as a dependent variable to reveal any possible relationships between response
209 accuracy and saccade/microsaccade orientation.

210 ***Pupil size characteristics.*** The raw data of the pupil diameters were normalised with z-scores
211 technique, by expressing every sample as a standard deviation score from the mean calculated within
212 each videoclip. Pupil size diameter was correlated with the duration of the corresponding videoclip,
213 from the trial start to goalkeepers' final movement initiation. Then, mean correlations were analysed
214 with a Paired sample t-test to investigate differences between penalty distances (11m; 6m).

215 Mauchly's test was used to assess any violations for sphericity. Effect size of the repeated measure
216 ANOVAs were expressed using partial eta-squared (η_p^2), with values of 0.01, 0.06, and 0.14
217 representing small, medium, and large effects respectively (Cohen, 1988). Statistical significance was
218 set at $p < 0.05$.

219 **Results**

220 After pre-processing data, in which responses shorter than 150 ms and longer than 250 ms (early or
221 delayed responses) were discarded (see Methods for description), 425 clips were retained for analysis
222 (of a total of 480; 55 clips were excluded).

223 ***Response accuracy and movement time***

224 In general, goalkeepers were significantly more accurate than not in predicting shot direction (57.08%
225 vs 42.91%; $F_{1,14} = 5.17$; $p = 0.039$; $\eta_p^2 = 0.27$). Analysis of variance did not show any significant
226 differences for the interaction effect between accuracy (predicted; missed) and condition (11m; 6m)
227 ($p = 0.36$). Paired sample t-test showed significant differences only for penalties kicked from 11m, in
228 which goalkeepers exhibited successfully predicted than missed penalties (60% vs 40%; $t(7) = 2.72$;
229 $p = 0.03$; $d = 1.93$, Figure 1A). No significant difference was found for predicted and missed penalties
230 kicked from 6m (54% vs 46%; $p = 0.43$), although there was an 8% improvement with a medium
231 effect size ($d = 0.59$).

232 Final movement time analysis showed a significant main effect for accuracy ($F_{1,7} = 14.07$; $p = 0.007$;
233 $\eta_p^2 = 0.67$), in which goalkeepers were slower when predicted compared to missed penalties (4706ms
234 vs. 4646ms). When penalties were kicked from 11m, goalkeepers were significantly faster when
235 missing and slower when successfully predicting penalties ($F_{1,7} = 9.19$; $p = 0.019$; $\eta_p^2 = 0.57$; Figure
236 1B).

237 *****Figure 1 near here*****

238 *Visual search order*

239 Analysis of the mean number of fixations showed significant increase for penalties from 11m in
240 comparison to penalties from 6m (2.61 vs 2.24; $t(7) = 3.74$; $p = 0.008$; $d = 1.32$). Repeated measures
241 ANOVA showed a significant condition x epoch interaction effect ($F_{3,42} = 9.61$; $p < 0.001$; $\eta_p^2 = 0.41$).
242 Paired sample t-test revealed significant increase for penalties from 11m in comparison to penalties
243 from 6m at the last epoch (4000ms; $t(7) = 2.81$; $p = 0.026$; $d = 1.05$; Table 1).

244 *****Table 1 near here*****

245 *Microsaccade/saccade characteristics*

246 Analysis of microsaccade rates showed a significant main effect for condition ($F_{1,14} = 4.82$; $p = 0.046$;
247 $n_p^2 = 0.26$) in which goalkeepers exhibited a greater rate during penalties kicked from 6m than from
248 11m (0.63 ± 0.19 vs 0.59 ± 0.18 number/sec).

249 Analysis of microsaccade rates time window showed significant main effect between the four-time
250 epochs ($F_{3,42} = 8.50$; $p < 0.001$; $n_p^2 = 0.38$) on each condition (Figure 2). Microsaccades rate analysed
251 during penalties kicked from 11m showed a decrement trend visible from the first to the last epoch
252 (Figure 2A; $p = 0.014$; $d = 1.27$). Looking at figure 2B, microsaccade rates decreased from the first
253 to the second epoch to about 33% ($p = 0.003$; $d = 1.49$), then 1000ms before goalkeeper's final
254 movement started, showed an additional decrease of about 53% with respect to the first epoch ($p =$
255 0.002 ; $d = 2.36$).

256 There were no significant differences between penalties kicked from 11m with respect to 6m for the
257 other microsaccade characteristics; duration (mean 39.54 vs 40.85 ms); amplitude (mean 0.64 vs
258 0.63° of visual angle) and peak velocity (mean 43.12 vs 39.95° /second).

259 Microsaccade durations showed a significant main effect for response accuracy ($F_{1,14} = 5.51$; $p =$
260 0.034 ; $n_p^2 = 0.28$), with longer duration in predicted than missed penalties (38.71 vs 36.85 ms).

261 *****Figure 2 near here*****

262 Analysis of saccade rates showed significant main effect for condition ($F_{1,14} = 4.27$; $p = 0.044$; $n_p^2 =$
263 0.25), with increased rate in penalties from 11m in comparison to penalties from 6m (1.27 vs 1.03
264 number/sec). A significant main effect was found for response accuracy ($F_{1,14} = 10.93$; $p = 0.005$; n_p^2
265 $= 0.44$), with higher saccade rates during predicted than missed penalties (1.18 vs 1.07 number/sec).

266 Analysis of saccade rates time window showed significant main effect between the four epochs ($F_{3,42}$
267 $= 31.01$; $p < 0.001$; $n_p^2 = 0.70$) on each condition. Saccade rates were almost stable for 3000 ms ($p =$
268 0.15 ; $d = 0.08$) in both conditions, increasing in the last epoch ($p < 0.001$; $d = 3.05$), reaching the
269 peak at about 500ms just before the goalkeeper's final movement started (Figure 3).

270 There were no significant differences between penalties kicked from 11m compared with penalties
271 kicked from 6m for the other saccade characteristics; duration (105.48 vs. 102.58 ms); amplitude
272 (3.57 vs. 3.82° of visual angle) and peak velocity (117.22 vs. 120.10°/second).

273 *****Figure 3 near here*****

274 ***Microsaccade/saccade orientation***

275 Microsaccades orientations were not significantly different comparing penalties from 11m with those
276 from 6m (103.70±11.50° vs. 90.45±8.29°, respectively; $p = 0.39$). It seems that, in both situations,
277 goalkeepers, during fixations, shift their covert attention from the lower to the upper kicker's body.

278 Saccade orientation showed a significant main effect for condition ($F_{1,14} = 40.52$; $p < 0.001$; $\eta_p^2 =$
279 0.74), with a main vector directed to the left during penalties kicked from 11m (222.12±7.21°), and
280 a main vector directed to the right during penalties kicked from 6m (323.25±13.17°) (Figure 4 lower
281 panel). It seems that the different angles of approaching the ball (left versus right) influences the
282 saccades orientation.

283 No significant difference was observed for response accuracy (predicted; missed) on
284 saccade/microsaccade orientations ($p > 0.05$).

285 *****Figure 4 near here*****

286 ***Pupil size characteristics***

287 Pupil dimension showed a significant correlation with the proximity to the movement time initiation
288 in both penalty conditions. Comparing the correlation values between penalties kicked from 11m with
289 respect to penalties kicked from 6m we found a significant difference ($r^2 = 0.98$ and 0.93 ; $t(7) = 3.40$;
290 $p = 0.011$; $d = 0.50$). Pupils increased as the goalkeepers' perception of the penalty taker's intention
291 developed, reaching the greatest value just before the goalkeepers' final movement initiation, and it
292 was significantly higher during penalties kicked from 11m compared to 6m (Figure 5).

293 *****Figure 5 near here*****

294 Additionally, both curves, represented by the right pupil size, were computed by measurements of
295 the area under the curve (AUC) at the intervals 2000–3400 ms, using the trapezoid rule (technique to
296 calculate the definite integral, approximating the region under the graph of the function as a trapezoid
297 and calculating its area). Analysis showed a significantly different area under the curves ($p < 0.001$),
298 with a mean value of 343 for penalties from 6m and a mean value of 559 for penalties from 11m. As
299 showed in Figure 5, in the other part of the temporal sequence the lines were totally (after 3400 ms)
300 or partially (before 2000ms) overlapped.

301 **Discussion**

302 The aim of the present study was to investigate the visual search strategy of soccer goalkeepers
303 engaged in penalties kicked from different distances (11m vs. 6m). Our hypothesis was that athletes,
304 during the period that precedes the final movement time initiation, adopted a different visual search
305 strategy dependent on situational constraints, with more microsaccades and less saccades during near
306 in comparison to far action.

307 During penalties kicked from 11m, goalkeepers exhibited a microsaccades rate time window with a
308 decrement trend visible from the first to the last epoch. Whereas, during penalties kicked from 6m,
309 microsaccade rates decreased from the first to the second epoch to about 33%, then 1000ms before
310 goalkeeper's final movement started, exhibited an additional decrease of about 53% with respect to
311 the first epoch (Figure 2). Saccade rate exhibited a similar trend in both 6m and 11m conditions,
312 almost stable for 3000 ms, with an increment in the last epoch, that reach the peak at about 500ms
313 just before the goalkeeper's final movement started, in concomitant with microsaccades reduction
314 (Figure 3). The current research supports previous literature (Piras et al., 2015, 2019, 2020; Piras,
315 Raffi, et al., 2016) highlighting how microsaccades can be suppressed with the increment of the
316 attentional resource during cognitive visual tasks, leading toward intrusion of small-saccades, which
317 could have the function to shift the attention to cues spatially related.

318 Comparing mean number of fixations, saccade and microsaccade rates between conditions,
319 goalkeepers in the 11m condition used a visual search strategy with more fixations, and consequently
320 greater saccade rates in comparison to penalties from 6m, where they exhibited fewer fixations and
321 higher microsaccade rates. The most fixated area during the last epoch before the goalkeepers' final
322 movement time initiation was significantly different between conditions. During penalties kicked
323 from 11m, fixations were located on the visual pivot, a location between the ball and the kicking
324 action (Piras & Vickers, 2011), meanwhile, from 6m, goalkeepers' fixations were located on the
325 kicker's legs (Table 1). Frequent fixations on the visual pivot could be explained by important cues
326 in close proximity to each other that need to be processed via the fovea, with areas inside the pivot
327 characterized by a minimal retinal distance with respect to the fovea (Vater et al., 2019). The
328 functionality of the visual pivot would be to hold the gaze on a location close to relevant cues and
329 initiate small saccades to these cues. During 6m condition, goalkeepers "anchored" their gaze to
330 kicker's legs, a position that optimizes information processing via peripheral vision, in which covert
331 attention is distributed to peripheral cues and eliminates the costs associated with saccadic eye-
332 movements. We can postulate that this could be due to the kicker's and ball different distance, which
333 influence the dimension of the images perceived (kicker and ball); as long as the opponent's distance
334 is large and thus time pressure reduced, gaze can be frequently shifted between the kicker's body and
335 the ball because the costs of saccades are low. On the contrary, closer objects require both foveal and
336 parafoveal to be stimulated for catching information (Williams et al., 2004). Indeed, when the
337 opponent is closer to the observer and time pressure increases, the opponent's body (i.e. the kicker's
338 legs) could turn into a gaze anchor (Piras, Pierantozzi, et al., 2014), where saccades are reduced, and
339 the fovea is not the only important aspect to acquire visual information since it becomes necessary to
340 monitor different cues with the parafovea (likely using microsaccades or small-saccades).

341 Vater and co-workers (2019) have postulated a theory in which saccades could be considered as a
342 relevant measure to distinguish between gaze anchor (saccade-avoiding) and visual pivot (saccade-

343 preparing), considering that pivots are thought to be optimal locations to initiate saccades to other
344 cues, and frequent saccades to the pivots can be predicted. In agreement with this theory, we identify
345 that during anchoring, experts make micro-saccades to take peripheral information, meanwhile,
346 during pivoting the same subjects produce small saccades to near areas. In this scenario of adapted
347 gaze strategy, the locus of covert attention is more relevant rather than the location (overt attention)
348 of gaze per se (Vater et al., 2019). Therefore, microsaccades with high frequency may suggest
349 attention to peripheral target due to pick up of relevant information, hence a very precise fixation may
350 not be necessary (Piras et al., 2015, 2019). Additionally, it appears that saccades are made in situations
351 with low time pressure to process information in regions of high acuity, in contrast to situations with
352 increased time pressure, where gaze-anchoring behavior is preferred due to the possibility of utilizing
353 microsaccades and avoiding saccades that could compromise the processing of the visual cue(s). The
354 key issue in light of the current discussion is that players demonstrate different visual search
355 behaviours under changing task constraints.

356 Williams et al. (2004) hypothesized that during a soccer match, when the distance between the ball
357 and the player is great, such as during 11vs11 open-play situation in soccer, players have time to
358 undertake a comprehensive analysis of the situation and seem to rely on information extraction via
359 the fovea. In contrast, when the ball is closer and the time constraints more critical, such as during
360 small-sided games (e.g. 1vs1), both fovea and peripheral vision may be employed, with players
361 initially using the fovea to extract relevant task information, while as the opponent approaches they
362 may rely more on peripheral vision to pick up the relative movement pattern. The emergent search
363 pattern in these situations would appear to be at least partly constrained by the number of players
364 involved in the action (they studied 11vs11; 3vs3 and 1v1 soccer situations) and the relative distance
365 between these players and the ball (Williams et al., 1994; Williams & Davids, 1998). Nevertheless,
366 authors did not consider that in details, such as the distance between players or the distance between
367 players and the ball. Moreover, they did not assess the subtle eye movements, which occur to provide

368 important visual information in determining appropriate subsequent decisions (Piras et al., 2020). As
369 postulated by the authors, empirical evidence is needed to clarify and support a constraints-based
370 explanation of visual search behaviour in sports (Williams et al., 2004). Consequently, our work
371 extends the important works of Williams et al. (1994; 1998), highlighting the important role of
372 microsaccades and the small-saccades, necessary to indicate both the locus of fixation and the locus
373 of attention in team game context.

374 The ability to quickly shift attention from one relevant cue to another is a prerogative of the athletes
375 (Piras et al., 2015). A recent study found that microsaccades provide a mechanism for precisely
376 relocating gaze in high-acuity tasks, supporting the proposal that microsaccades are exploratory
377 movements, similar to larger saccades (Ko et al., 2010). In a sport situation, Piras et al. (2020) found
378 a significant difference in microsaccade angular orientations during penalties kicked from 11m,
379 showing that microsaccades could anticipate the goalkeeper's intention. Therefore, we have
380 compared the microsaccade angular directions during penalties from 11m with that of penalties from
381 6m, demonstrating that the main vector has the same direction in both conditions (Figure 4). It could
382 indicate that athletes shift their attention from the lower (legs; visual pivot) to the upper opponent's
383 body (trunk; head) (Piras et al., 2015). Meanwhile, saccades direction during penalty kicked from 6m
384 showed a mean angular direction toward the lower right of the goalkeeper's visual field (Figure 4
385 lower panel). At this point, we can confirm, in combination with the previous study (Piras et al.,
386 2020), that saccade orientations are conditioned by the penalty taker's body movement, following the
387 direction of the kicker during their approach (run-up) toward the ball.

388 Pupil size is an effective indicator of cognitive load (Krejtz et al., 2018), and has been associated with
389 motor preparation (Jainta et al., 2011). In the current study, we specifically examined pupil dynamics
390 during a sport situation where the appropriate allocation of visual attention precedes and determines
391 effective motor behaviour. The pupils dilated relatively more during the viewing of small objects
392 visualized at a relatively far distance than at a near distance. It has also been found that the pupil

393 diameter changed with the scope of attention, dilating with broadly spread attention and contracting
394 with narrowly focused attention (Daniels et al., 2012). Interestingly, in the present study, when the
395 goalkeeper saw the pattern enlarging on screen as the kicker approached the ball, pupil diameter
396 increased over time (Piras et al., 2020). Overall, the results of the area under the curve at a specific
397 intervals (2000–3400 ms) showed that pupil size prior to stimulus presentation effectively reflected
398 preparatory set activity related to saccade initiation, and confirmed a direct link between saccade
399 initiation and pupil size (Wang & Munoz, 2015). This increase in pupil diameter could increase visual
400 sensitivity to improve perceptual processes immediately after to redirect the eyes (Piras et al., 2020).

401 In general, we found successfully predicted than missed penalties (57% vs 43%). When the
402 goalkeeper's final movement time initiated in a time equal or slightly greater than 4.7 seconds, the
403 probability to predict the ball increased. Conversely, faster responses, below 4.7 seconds, raised the
404 probability to miss the direction of the ball at both distances. Moreover, we should consider that from
405 11m, GKs exhibited successfully predicted than missed penalties (60% vs 40%). At 6m, whilst there
406 was no significant difference for predicted and missed penalties, there was an 8% improvement with
407 a medium effect size ($d = 0.59$). So, in both penalty distances, GK's were better in predicting than
408 missing, suggesting that they had suitable experience in both environments. This slight reduction in
409 number of predicted penalties at 6m compared to 11m could be attributed to the recreational practice
410 of our goalkeepers, that was more frequent at 11m compared to 6m, therefore, they may have been
411 more familiar with this condition. Additionally, it has been largely demonstrated that it is more
412 difficult to intercept the ball kicked closer than farther, even in the same environment (Navia et al.,
413 2017).

414 Within the design of the current study, we acknowledge the following limitations. In line with the
415 power analysis, 8 goalkeepers were recruited to the study. Whilst this sample may appear small, it
416 was important to recruit participants of a similar (national level) ability to ensure a homogenous

417 group. Future research may wish to consider how saccades and microsaccades differ as a function of
418 expertise. Second, we presented the right footed penalty taker from a soccer pitch and the left footed
419 penalty taker from the futsal pitch. We decided against presenting a mix of right and left foot penalty
420 kicks for both distances as our intention was not to determine if goalkeepers were more able to
421 intercept the ball kicked with the left or with the right in different distances. Adding additional trials
422 into the study design would have also required a larger sample size, which was not possible. Third,
423 there were differences in ambient conditions between the soccer pitch and the futsal pitch. Whilst it
424 would have been possible to use the same environment (record only from the identical soccer or futsal
425 pitch, just at different distances), this would have impacted the representative nature of the study (c.f.
426 Araújo et al., 2007); moving a soccer ball closer (to 6m) and filming on a soccer pitch (or vice-versa
427 for futsal) was not representative of what a goalkeeper experiences in their natural environment.

428 In conclusion, when the spatiotemporal constraint is less severe, as it was during penalties from 11m,
429 the goalkeepers exhibit a visual search strategy based on more fixations and small saccades to pick
430 up relevant information from the fovea. When the spatiotemporal constraint is more severe (6m
431 condition), goalkeepers relied on peripheral vision to monitor kicker's movements through the use of
432 microsaccades, due to their increased ability to bring the neuronal receptive fields to stimulus regions.

433 **Disclosure statement**

434 No potential conflict of interest was reported by the authors.

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538

539 **Figure captions**

540 **Figure 1.** Histograms represent the percentage values between predicted (in black) and missed (in
541 grey) penalty kicks across condition (11m and 6m) (A); and the response time of the goalkeepers
542 between predicted (in black) and missed (in grey) penalty kicks across condition (11m and 6m) (B).

543 **Figure 2.** Time course of microsaccade rates during penalties kicked from 11m (A) and from 6m (B),
544 calculated from the goalkeeper's final movement initiation to backwards for 4000ms. Rates were
545 computed for each GKs using a moving time window of 200ms and then averaged over all athletes.
546 Solid black lines represent the mean rate, meanwhile the shaded grey areas represent the standard
547 error of the mean.

548 **Figure 3.** Time course of saccade rates during penalties kicked from 11m (A) and from 6m (B),
549 calculated from the goalkeeper's final movement initiation to backwards for 4000ms. Rates were
550 computed for each GKs using a moving time window of 200ms and then averaged over all athletes.
551 Solid black lines represent the mean rate, meanwhile the shaded grey areas represent the standard
552 error of the mean.

553 **Figure 4.** Panels represent the direction of the mean vector of microsaccades (upper) and saccades
554 (lower) across conditions (11m; 6m). each angular sector is 22.50° in width. Radial thick lines are the

555 mean vectors, curved lines external to the diagrams indicate the standard deviation, with the 95% of
556 confidence interval ($p < 0.05$).

557 **Figure 5.** Plot show the pupil size dilations of all GKs during penalties kicked from 11m (solid grey
558 line) and penalties kicked from 6m (dotted black line), correlated with the trial time until the
559 goalkeeper's final movement initiation.

Table 1. Mean Number of Fixations and interest areas

Epochs								
	1000 ms		2000 ms		3000 ms		4000 ms	
	No. of fix	IAs	No. of fix	IAs	No. of fix	IAs	No. of fix	IAs
11m	2.49±0.53	Trunk	2.51±0.48	Legs	2.25±0.32	Trunk	2.97±0.39	Visual Pivot
6m	2.60±0.95	Legs	2.51±0.84	Legs	2.24±0.76	Trunk	2.53±0.44	Legs
<i>p</i> -value	0.323		0.492		0.464		0.025*	
Cohen's <i>d</i>	0.12		0.12		0.14		1.05	

Mean (\pm SD) number of fixations on each interest areas (IAs) across epochs between conditions. Asterisk indicates significant differences at $p < 0.05$

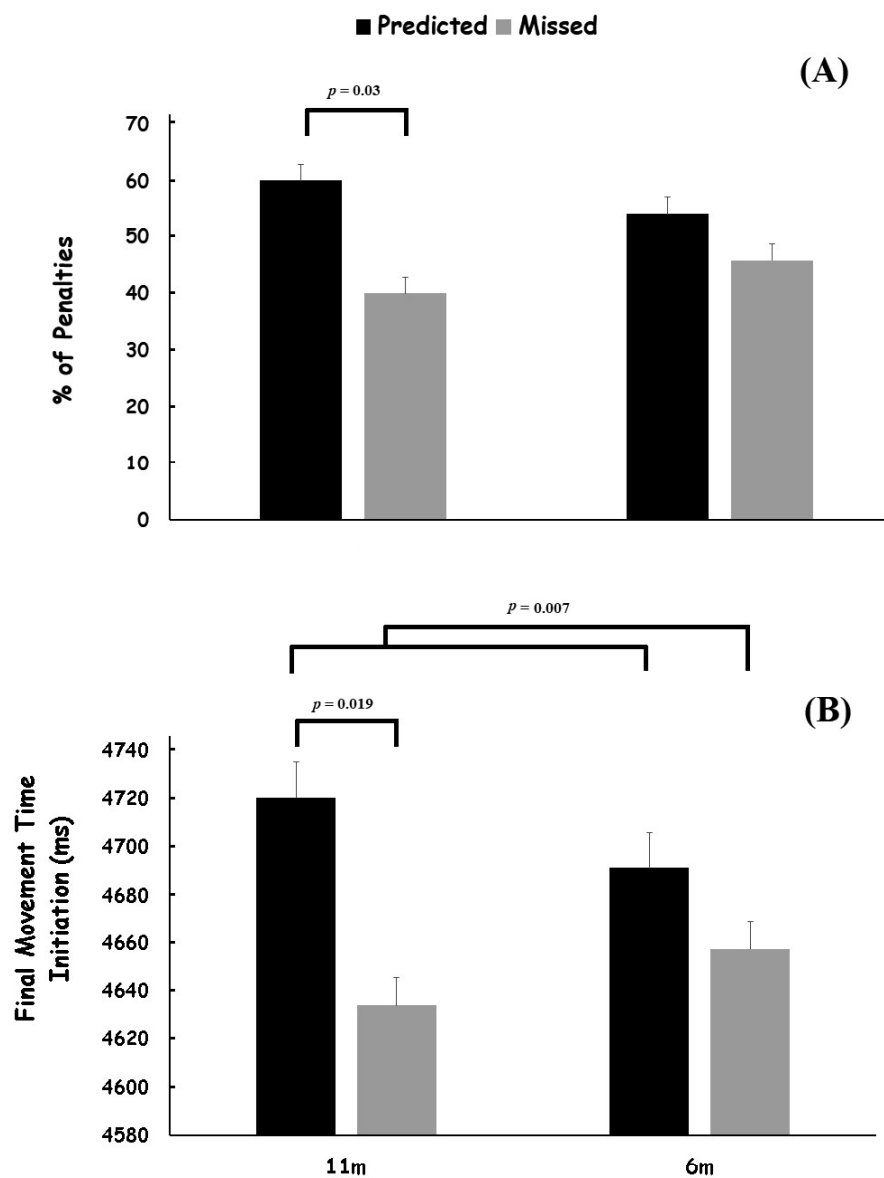


Figure 1. Histograms represent the percentage values between predicted (in black) and missed (in grey) penalty kicks across condition (11m and 6m) (A); and the response time of the goalkeepers between predicted (in black) and missed (in grey) penalty kicks across condition (11m and 6m) (B).

42x56mm (600 x 600 DPI)

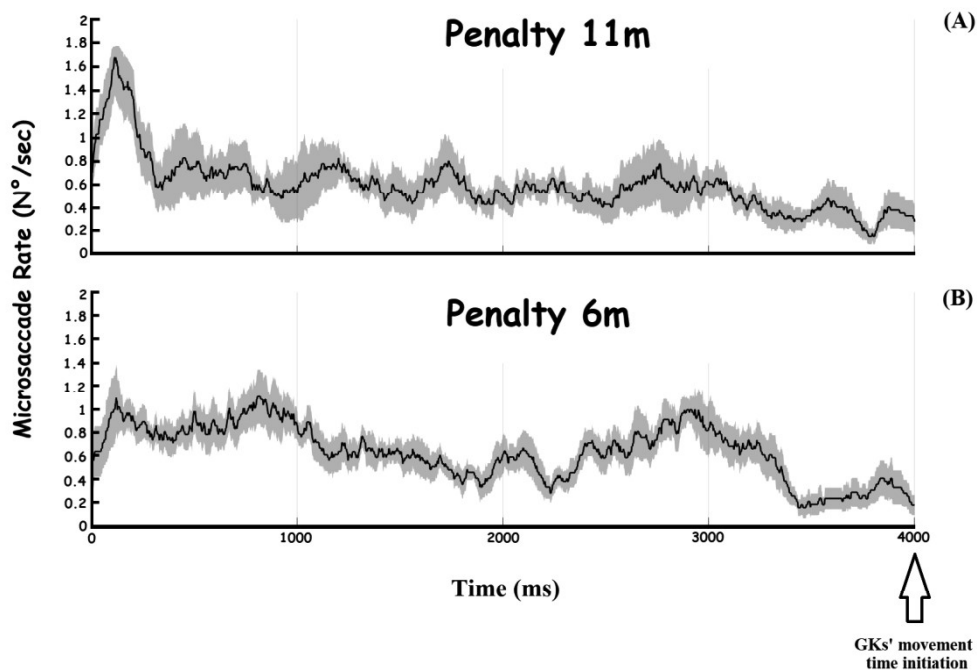


Figure 2. Time course of microsaccade rates during penalties kicked from 11m (A) and from 6m (B), calculated from the goalkeeper's final movement initiation to backwards for 4000ms. Rates were computed for each GKs using a moving time window of 200ms and then averaged over all athletes. Solid black lines represent the mean rate, meanwhile the shaded grey areas represent the standard error of the mean.

72x50mm (600 x 600 DPI)

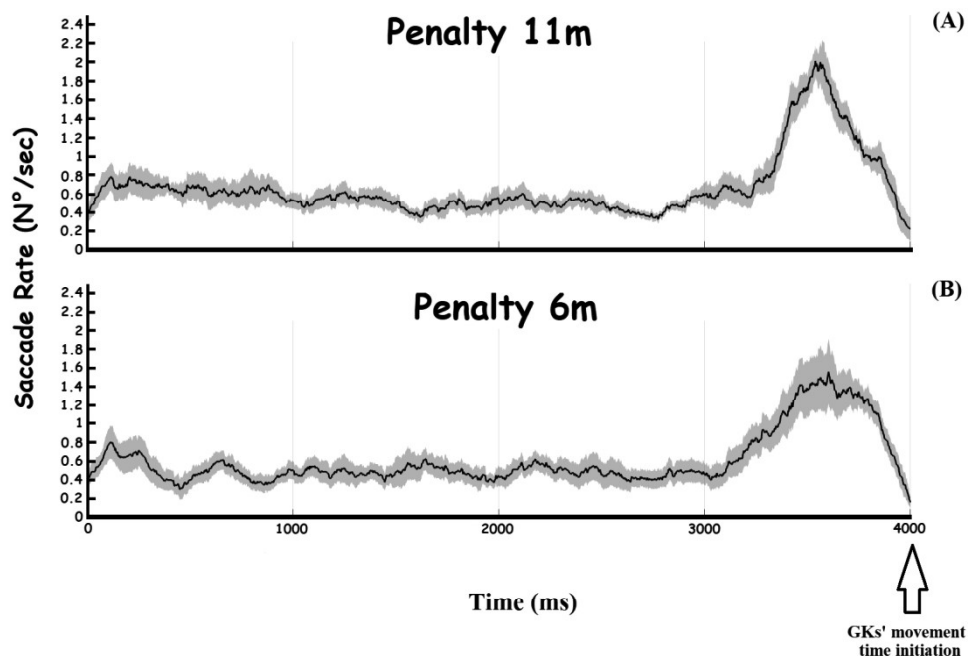
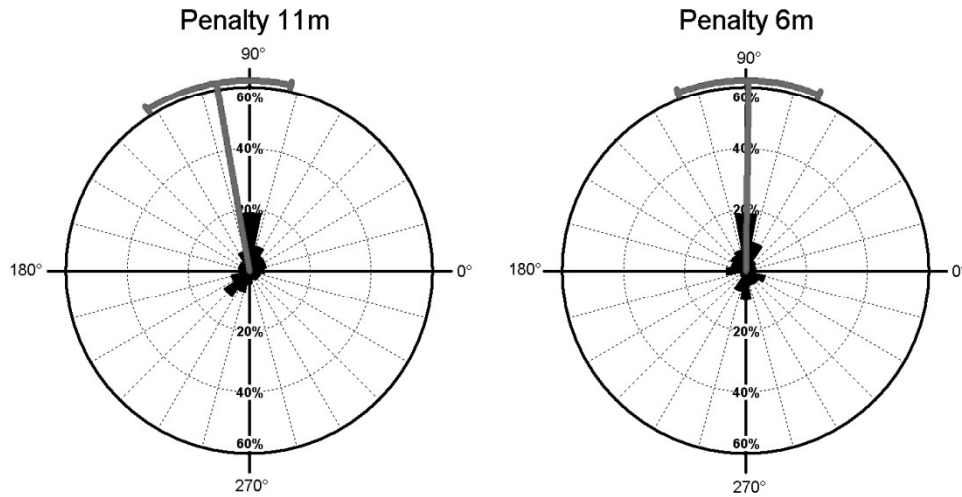


Figure 3. Time course of saccade rates during penalties kicked from 11m (A) and from 6m (B), calculated from the goalkeeper's final movement initiation to backwards for 4000ms. Rates were computed for each GKs using a moving time window of 200ms and then averaged over all athletes. Solid black lines represent the mean rate, meanwhile the shaded grey areas represent the standard error of the mean.

72x50mm (600 x 600 DPI)

Microsaccades



Saccades

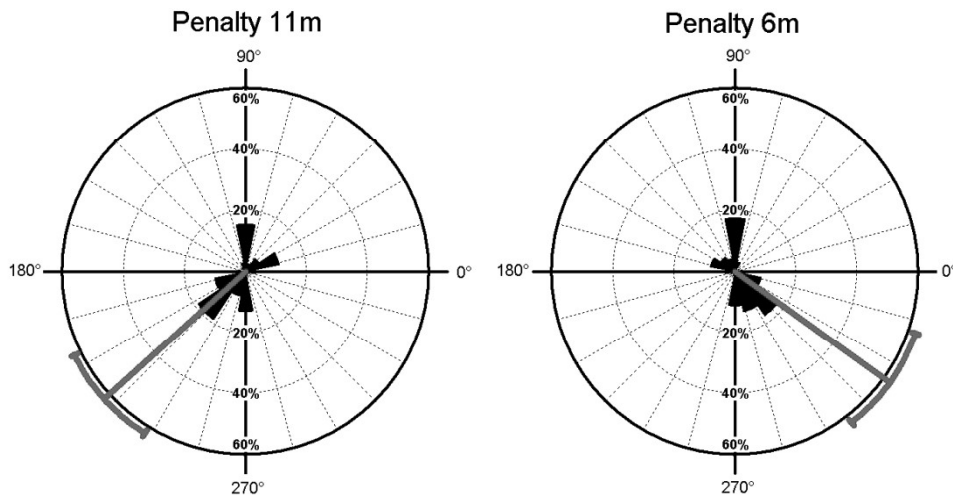


Figure 4. Panels represent the direction of the mean vector of microsaccades (upper) and saccades (lower) across conditions (11m; 6m). each angular sector is 22.50° in width. Radial thick lines are the mean vectors, curved lines external to the diagrams indicate the standard deviation, with the 95% of confidence interval ($p < 0.05$).

60x73mm (600 x 600 DPI)

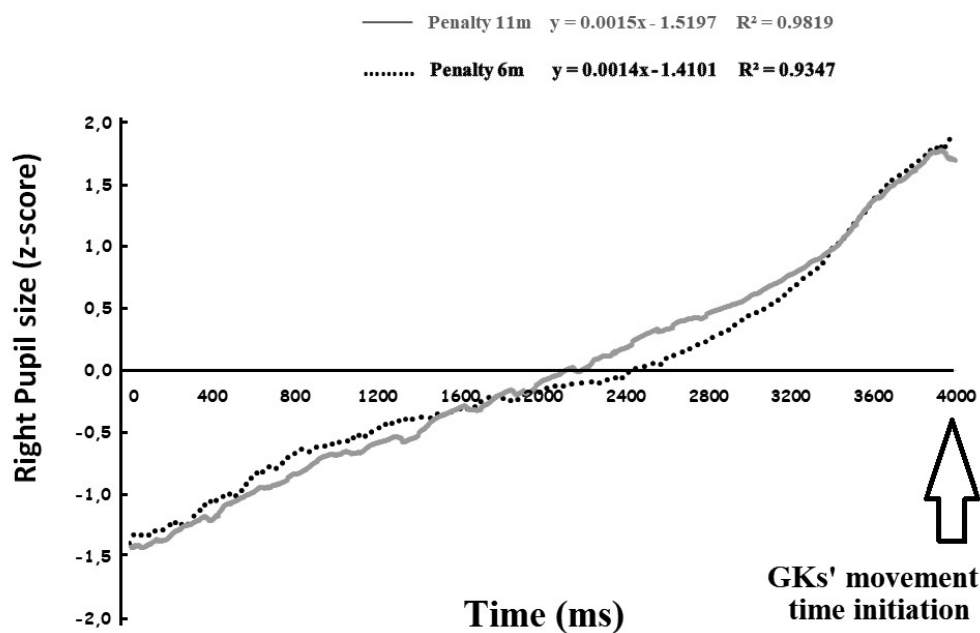


Figure 5. Plot show the pupil size dilations of all GKs during penalties kicked from 11m (solid grey line) and penalties kicked from 6m (dotted black line), correlated with the trial time until the goalkeeper's final movement initiation.

40x27mm (600 x 600 DPI)